Bi-Stable Display with DC-Balanced Over-Reset Driving

The invention relates generally to electronic reading devices such as electronic books and electronic newspapers and, more particularly, to a method and apparatus for updating images with improved image quality and reduced update time using both monochrome and grayscale images.

Recent technological advances have provided "user friendly" electronic reading devices such as e-books that open up many opportunities. For these uses, electrophoretic displays hold much promise. Such displays have an intrinsic memory behavior and are able to hold an image for a relatively long time without power consumption. Power is consumed only when the display needs to be refreshed or updated with new information. The power consumption in such displays is very low, suitable for applications for portable e-reading devices like e-books and e-newspapers. Electrophoresis takes place in movement of charged particles in an applied electric field. When electrophoresis occurs in a liquid, the particles move with a velocity determined primarily by the viscous drag experienced by the particles, their charge (either permanent or induced), the dielectric properties of the liquid, and the magnitude of the applied field. An electrophoretic display is a type of bi-stable display, which is a display that substantially holds an image without consuming power after an image update.

An electrophoretic display comprises an electrophoretic medium ("electronic ink") containing charged particles in a fluid, a plurality of display elements (pixels) arranged in a matrix, first and second electrodes associated with each pixel, and a voltage driver for applying a potential difference to the electrodes of each pixel to cause charged particles to occupy a position between the electrodes, depending on the value and duration of the applied potential difference, so as to display an image or other information.

For example, international patent application WO 99/53373, published April 9, 1999, by E Ink Corporation, Cambridge, Massachusetts, US, and entitled Full Color Reflective Display With Multichromatic Sub-Pixels, describes such a display device.

WO 99/53373 discusses an electronic ink display having two substrates. One is transparent, and the other is provided with electrodes arranged in rows and columns. A display element or pixel is associated with an intersection of a row electrode and column electrode. The display element is coupled to the column electrode using a thin film transistor (TFT), the gate of which is coupled to the row electrode. This arrangement of display elements, TFT transistors, and row and column electrodes together forms an active matrix. Furthermore, the display element comprises a pixel electrode. A row driver selects a row of display elements, and a column or source driver supplies a data signal to the selected row of display elements via the column electrodes and the TFT transistors. The data signals correspond to graphic data to be displayed, such as text or figures.

The electronic ink is provided between the pixel electrode and a common electrode on the transparent substrate. The electronic ink comprises multiple microcapsules of about 10 to 50 microns in diameter. In one approach, each microcapsule has positively charged white particles and negatively charged black particles suspended in a liquid carrier medium or fluid. When a positive voltage is applied to the pixel electrode, the white particles move to a side of the microcapsule directed to the transparent substrate and a viewer will see a white display element. At the same time, the black particles move to the pixel electrode at the opposite side of the microcapsule where they are hidden from the viewer. By applying a negative voltage to the pixel electrode, the black particles move to the common electrode at the side of the microcapsule directed to the transparent substrate and the display element appears dark to the viewer. At the same time, the white particles move to the pixel electrode at the opposite side of the microcapsule where they are hidden from the viewer. When the voltage is removed, the display device remains in the acquired state and thus exhibits a bi-stable character. In another approach, particles are provided in a dyed liquid. For example, black particles may be provided in a white liquid, or white particles may be provided in a black liquid. Or, other colored particles may be provided in different colored liquids, e.g., white particles in green liquid.

Other fluids such as air may also be used in the medium in which the charged black and white particles move around in an electric field (e.g., Bridgestone SID2003

– Symposium on Information Displays. May 18-23, 2003, - digest 20.3). Colored particles may also be used.

To form an electronic display, the electronic ink may be printed onto a sheet of plastic film that is laminated to a layer of circuitry. The circuitry forms a pattern of display elements (pixels) that can then be controlled by a display driver. Since the microcapsules are suspended in a liquid carrier medium, they can be printed using existing screen-printing processes onto virtually any surface, including glass, plastic, fabric and even paper. Moreover, the use of flexible sheets allows the design of electronic reading devices that approximate the appearance of a conventional book.

Further advancements are needed to improve image quality and reduce image update time.

One of the major challenges in the research and development of an electronic ink type electrophoretic display is to achieve accurate gray levels, which are generally created by applying voltage pulses for specified time periods. The accuracy of the greyscales in electrophoretic displays is strongly influenced by image history, dwell time, temperature, humidity, lateral inhomogeneity of the electrophoretic foils etc. The accurate grey levels can be achieved using rail-stabilized approach, which means that the grey levels are reached either from reference black or from reference white state (the two rails).

The present invention provides a solution that overcomes these problems related to achieving accurate gray scale and other problems encountered in prior art bi-stable displays.

In one aspect, the present invention relates to a method for addressing a bi-stable display element using a rail-stabilized driving scheme with DC-balanced over-reset pulse, in, in particular, an electrophoretic display with at least two bits grayscale. The reset impulse has both “standard reset” and “over-reset” components, regardless of the image update sequence. The “standard reset” impulse (involved energy) is proportional to the distance required for the electronic ink to move to a rail.

For example, when pulse width modulation (PWM) driving is used, the full pulse width (FPW) is required for resetting the display from white to black and only 2/3 of the FPW is needed from light gray to black and 1/3 of the FPW from dark gray to black. This standard reset pulse time is naturally zero from black to black. A

constant "over-reset" impulse must, however, be chosen independently of the distance that ink needs to move during reset. If, for example, the display is to be reset to black state from white, light gray, dark gray or black, a constant over-reset impulse must be applied, including the reset from black to black. When the above total reset impulse is symmetrically applied to both black and white, the driving is ideally DC-balanced. A rail-stabilized driving scheme with DC-balanced over-reset pulse is thus implemented for an electrophoretic display with at least two bits grayscale.

In another aspect, the present invention relates to a method of addressing a bi-stable display element using an over-reset pulse for DC-balancing of the display element. The DC-balancing is such that the average potential difference applied to the display element over a time period is zero. For example, after an irreversible loop: white to dark gray to white, the net DC on the pixel should be zero. The grayscale driving pulses are adjusted accordingly to take into account the DC-balancing. Not only are the over-reset pulses adjusted for DC balancing, but the DC-balancing applied by the over-reset to a display element is also reflected in the proration of the FPW.

These and other aspects of the invention will be apparent from and elucidated with reference to the embodiment(s) described hereinafter.

In the drawings:

FIG. 1 is a diagrammatic cross-section of a portion of a display device.

FIG. 2 is an equivalent circuit diagram of a portion of a display device.

FIG. 3 illustrates a prior art driving method.

FIG. 4 shows a first embodiment of a driving scheme according to this invention using pulse width modulation (PWM) driving.

FIG. 5 shows a second embodiment using PWM driving without a second series of shaking pulses.

FIG. 6 shows a third embodiment in which PWM driving is used without a first series of shaking pulses.

FIG. 7 shows a fourth embodiment using PWM driving without a first or second series of shaking pulses.

FIG. 8 shows a fifth embodiment using PWM driving with additional shaking pulses in short sequences.

FIG. 9 shows a sixth embodiment using PWM driving to achieve DC-balancing in a white-dark gray-white loop for a practically imperfect ink material (sensitive to dwell time and image history.).

The Figures are schematic and not drawn to scale, and, in general, like reference numerals refer to like parts.

FIG. 1 is a diagrammatic cross-section of a portion of an electrophoretic display device **101**, for example of the size of a few display elements **118**, each comprising a base substrate **102**, an electrophoretic film with an electronic ink which is present between two transparent substrates **103**, **104** of, for example, polyethylene. One of the substrates **103** is provided with transparent pixel electrodes **105** and the other substrate **104** is provided with a transparent counter electrode **106**. The electronic ink comprises multiple microcapsules **107** of about 10 to 50 microns. Each microcapsule **107** comprises positively charged white particles **108** and negatively charged black particles **109** suspended in a fluid **110**. When a negative field is applied to the counter electrode **106**, the white particles **108** move to the side of the microcapsule **107** directed to the counter electrode **106**, and the display element **118**, here comprising the counter electrode **106**, pixel electrode **105** and microcapsule **107**, becomes visible to a viewer. Simultaneously, the black particles **109** move to the opposite side of the microcapsule **107** where they are hidden from the viewer. By applying a positive field to the counter electrodes **106**, the black particles **109** move to the side of the microcapsule **107** directed to the counter electrode **106**, and the display element appears dark to a viewer (not shown). When the electric field is removed, the particles **107** remain in the acquired state and the display exhibits a bi-stable character and consumes substantially no power.

FIG. 2 is an equivalent circuit diagram of a picture display device **201** comprising an electrophoretic film laminated on a base substrate **202** provided with active switching elements, a row driver **216** and a column driver **225**. Preferably, a counter electrode **206** is provided on the film comprising the encapsulated electrophoretic ink, but could be alternatively provided on a base substrate in the case of operation with in-plane electric fields. The display device **201** is driven by active switching elements, in this example thin-film transistors **219**. It comprises a matrix of display elements at the area of crossings of row or selection electrodes **217** and

column or data electrodes **211**. The row driver **216** consecutively selects the row electrodes **217**, while a column driver **225** provides a data signal to the column electrode **211**. Preferably, a controller **215** first processes incoming data **213** into the data signals. Mutual synchronizations between the column driver **225** and the row driver **216** takes place via drive lines **212**. Select signals from the row driver **216** select the pixel electrodes **222** via the thin-film transistors **219** whose gate electrodes **220** are electrically connected to the row electrodes **217** and the source electrodes **221** are electrically connected to the column electrodes **211**. A data signal present at the column electrode **211** is transferred to the pixel electrode **222** of the display element coupled to the drain electrode via the TFT. In the embodiment, the display device of **FIG.1** also comprises an additional capacitor **223** at the location of each display element **218**. In this embodiment, the additional capacitor **223** is connected to one or more storage capacitor lines **224**. Instead of TFTs, other switching elements can be used, such as diodes, MIMs, etc.

FIG. 3 illustrates a prior art driving method. A driving method of this kind using a single over-reset voltage pulse has been found to be very promising for driving an electrophoretic display. Such a method is described in a prior, co-pending, non-prepublished application EP 03100133.2, filed January 23, 2003 (Applicants' docket no. PHNL030091). The horizontal direction in **FIG. 3** is time, with the sub-frame time (SFT) durations marked. The vertical direction is the amplitude of the potential difference applied to a display element. The duration **330** in **FIG. 3** is the total image update time. In this example, image updates to dark gray **G1** from light gray **G2** and white **W** and black **B** and dark gray **G1** are shown with reset pulses **338, 339** including over-reset. The pulse sequence typically has four portions: first shaking pulses **340, 341**, reset pulse **338, 339**, second shaking pulses **342, 343** and grayscale driving pulse **344, 345**. The sequences shown in **FIG. 3** are for image transition to dark gray **G1** from black **B**, dark gray **G1**, light gray **G2** and white **W**. Four transitions to **G1** state from **W, G2, G1, B** are realized using two types of pulse sequences using over-reset for resetting the display: There is a long sequence for the transitions from **G2** or **W** to **G1** and a short sequence for **G1** or **B** to **G1**. This method is, however, not DC-balanced.

FIG. 4 shows a first embodiment of a driving scheme according to the present invention, here using pulse width modulation (PWM) driving. The horizontal direction in **FIG. 4** indicates time, with the SFT durations marked. The amplitude of the potential difference applied to a display element is represented by the vertical dimension. The duration **430** in **FIG. 4** is the total image update time. The reset pulses **438** have two parts: the standard reset time **432, 433, 434** and the over-reset time **431** for the same types of image transitions as in **FIG. 3**, i.e. for the transitions from black **B**, dark gray **G1**, light gray **G2** and white **W** to dark gray **G1**. The over-reset time $t_{over\text{-}reset}$ **431** is constant regardless of the image transitions. The standard reset time **432, 433, 434** is proportional to the distance required for the particles in the electronic ink to move in a direction at a right angle to the substrates of the display (**102, 103, 104** in **FIG. 1**), indicated as times t_1 **432**, t_2 **433** and t_3 **434** for transitions from **W**, **G2** and **G1** to **G1** respectively. Short sequences **446, 447, 448** during which no voltage is applied to the display element are created by setting the standard reset time **432, 433, 434** according to the distance the particles are to move.

This first embodiment schematically shown in **FIG. 4** is of a display having at least 2-bits gray levels: black **B**, dark gray **G1**, light gray **G2** and white **W**. Four types of pulse sequences are used for the four different transitions to **G1** state from **W, G2, G1, B** and each sequence has four portions: first shaking pulses **440**, reset **438**, second shaking pulses **442** and driving **444**. Usually, t_1 **432** is equal to the saturation time which is the minimum time required for switching the display from full black to full white. t_2 **433** is the subtraction of the saturation time and the time used in the previous grayscale driving pulse from **W** to **G2**. t_3 **434** is equal to the time used in the previous grayscale driving pulse from **B** to **G1**. In an ideal case, the grayscale driving pulses for **W** to **G2** or **B** to **G1** have a pulse period 1/3 of the saturation time t_1 **432**. t_2 **433** becomes then 2/3 of t_1 **432**, and t_3 **434** becomes 1/3 of t_1 **432**. Meanwhile, $t_{over\text{-}reset}$ **431** is always the same in all image transitions including reset from black to black or white to white. When the same principle is applied for the image transitions via opposite rail, a completely symmetric driving is realized, which is ideally DC-balanced.

FIG. 5 illustrates a second embodiment according to this invention in which PWM driving is also used, but the second shaking pulses **442** of the first embodiment

are absent. As in **FIG. 3** and **FIG. 4,** the horizontal direction in **FIG. 5** represents time, with the SFT durations marked. The vertical direction represents the amplitude of the potential difference applied to a display element. The duration **530** in **FIG. 5** is the total image update time. The reset pulses **538** have two parts: the standard reset time **532, 533, 534** and the over-reset time **531** for the same types of image transitions as in **FIG.'s 3 and 4,** i.e. for the transitions from black **B,** dark gray **G1,** light gray **G2** and white **W** to dark gray **G1**. The over-reset time $t_{over\text{-}reset}$ **531** is constant regardless of the image transitions. Each sequence of potential differences here has only three portions: first shaking pulses **540,** reset **538** and driving **544**. Counterparts of the second series of shaking pulses **442** in **FIG. 4** are, however, not present in any of the transition sequences, **W, G2, G1, B** to **G1**. In this embodiment, the delay of the grayscale introduction is reduced, resulting in more natural image appearance. Also, the total image update time is shortened. The image quality from this embodiment would, however, be diminished in comparison to the first embodiment, because of stronger image retention when less shaking is used.

FIG. 6 illustrates a third embodiment according to this invention using PWM driving, which differs from the first embodiment in that the first series of shaking pulses, **440** in **FIG. 4**, is not present. As in **FIG. 4**, the horizontal direction in **FIG. 6** represents time, with the SFT durations marked. The vertical direction represents the amplitude of the potential difference applied to a display element. The duration **630** in **FIG. 6** is the total image update time. The reset pulses **638** have two parts: the standard reset time **632, 633, 634** and the over-reset time **631** for the image transitions from black **B,** dark gray **G1,** light gray **G2** and white **W** to dark gray **G1**. The over-reset time $t_{over\text{-}reset}$ **631** is constant regardless of the image transitions.

Each sequence of potential differences in **FIG. 6** has only three portions: reset **638,** second shaking **642** and driving **644**. The first shaking pulses (**440** in **FIG. 4**) have been removed from all transition sequences. The total image update time is shortened in this embodiment, but the image quality is diminished when compared to the first embodiment. As is the case with regard to the second embodiment discussed above, stronger image retention is expected if less shaking is used.

A fourth embodiment of the invention is schematically shown in **FIG. 7,** which is different from the first embodiment discussed above in that neither a first

series of shaking pulses (**440** in **FIG. 4**) nor a second series of shaking pulses (**442** in **FIG. 4**) are present in any of the transition sequences. As in **FIG.'s 4-6**, the horizontal direction in **FIG. 7** represents time, with the SFT durations marked. The vertical direction represents the amplitude of the potential difference applied to a display element. The duration **730** in **FIG. 7** is the total image update time. The reset pulses **738** have two parts: the standard reset time **732, 733, 734** and the over-reset time **731** for the image transitions from black **B**, dark gray **G1**, light gray **G2** and white **W** to dark gray **G1**. The over-reset time $t_{over\text{-}reset}$ **731** is still constant regardless of the image transitions.

Each sequence of potential differences in **FIG. 7** has only two portions: reset **738** and driving **744**. As with the second and third embodiments, the delay of the grayscale introduction in this embodiment is reduced, resulting in more natural image appearance. The total image update time is further shortened. The image quality is, however, diminished when compared to any of the above the embodiments, because stronger image retention is expected if less shaking is used.

FIG. 8 illustrates a fifth embodiment according to this invention. This fifth embodiment is based on the first embodiment, using PWM driving with additional shaking pulses **849, 850, 851** in the short sequences **846, 847, 848**, respectively. As in **FIG.'s 4-7**, the horizontal direction in **FIG. 8** represents time, with the SFT durations marked. The vertical direction represents the amplitude of the potential difference applied to a display element. The duration **830** in **FIG. 8** is the total image update time. The reset pulses **838** have two parts: the standard reset time **832, 833, 834** and the over-reset time **831** for the image transitions from black **B**, dark gray **G1**, light gray **G2** and white **W** to dark gray **G1**. The over-reset time $t_{over\text{-}reset}$ **831** is still constant regardless of the image transitions.

Each sequence of potential differences in **FIG. 8** has first shaking pulses **840**, reset **838**, second shaking pulses **842** and driving pulse **744**. The additional shaking pulses **849, 850, 851** for the image transitions from black **B**, dark gray **G1**, light gray **G2** to dark gray **G1** further reduce the image retention and increase the grayscale accuracy in comparison to any of the previous embodiments, without increasing the total image update time. For optimal image quality, it is preferable to fully fill in the time space between the first shaking pulses **840** and reset pulses **838** with the

additional shaking pulses **849, 850, 851**. These additional shaking pulses **849, 850, 851** may differ from the first shaking pulses **840** and second shaking pulses **842** in terms of the energy involved in an additional shaking pulse **849, 850, 851**. This fifth embodiment is apparently the most favorable embodiment for optimal picture quality but may consume more power.

In practice, because of image history, dwell time, inhomogeneity of the electrophoretic foils and other variables, driving of the display will rarely be ideally DC-balanced. A pixel can experience a net potential difference over a time period even if the changes in the optical state of a pixel are symmetrical during that time.

A practical example is illustrated in **FIG. 9**. As in **FIG.'s 4-8,** the horizontal direction in **FIG. 9** represents time, with the SFT durations **964** marked. The vertical direction represents the amplitude of the potential difference applied to a display element. The waveform sequence at the top in **FIG. 9** is an example of a DC-imbalanced **W-G1-W** loop. A sixth embodiment using PWM driving to achieve DC-balancing in the **W-G1-W** loop is shown by the waveform sequence at the bottom in **FIG. 9**. Each first waveform in **FIG. 9** has two portions, reset **938** and driving **944, 945**. The reset pulses **938** have two parts: the standard reset time **932, 933** and over-reset time **931, 941**. Here, the standard reset times **932, 933** are 300 ms. The over-reset time **931** for the DC-imbalanced **W-G1-W** loop is 100 ms. The over-reset time **941** for the DC-balanced **W-G1-W** loop is 150 ms. The standard reset times **960, 961** are 200 ms and the over-reset times **962, 963** are 100 ms for the transition from dark gray **G1** to white **W** for both the DC-unbalanced and DC-balanced **W-G1-W** loops.

In such practically imperfect ink material (sensitive to dwell time and image history), the dark grayscale drive pulse **944** is longer than the nominal pulse length needed for moving the particles from the black **B** to dark gray **G1** position. The pulse length of the dark grayscale drive pulse **944** is here supposed to be 100 ms. In practice, however, in the DC-imbalanced **W-G1-W** loop, 140 ms is needed to achieve the correct gray level, resulting in a net DC of 40 msX(-)V = -40ms. This may be caused by the fact that the brightness of the display is not only determined by the vertical position, but also by the exact configuration of the particles close to the position.

In order to balance this loop, one may intentionally add 50 ms of additional over-reset to the over-reset **941** in the **W** to **G1** transition and, in the mean time, only 10 ms needs to be added in the grayscale driving portion **945** to correct the brightness change induced by the additional reset. In this way, the whole loop is completely DC-balanced. Note that the standard reset and original over-reset in **G1** to **W** remain the same.

Thus, the present invention provides opportunities for improved DC-balancing in this situation. For example, for a display in which PWM is used to address image data to the pixels, the duration of the over-reset pulse may be varied, instead of being kept constant as is done in the first five embodiments, and that variation off-set by a smaller, additional variation in the grayscale driving time so that over time the potential difference applied to a pixel is averaged to zero. A change in the potential difference applied during the grayscale driving can compensate for, approximately, a five times larger adjustment in the potential difference applied during over-reset.

These embodiments are only some of the many possible applications of the invention in PWM driving.

The drive signal may consist of a pulse of fixed duration and varying amplitude e.g. voltage modulated (VM) driving, a pulse with a fixed amplitude, alternating polarity and a varying duration between two extreme values, and a hybrid drive signal, e.g. combined VM/PWM driving, wherein both the pulse length and the amplitude can be varied. For a pulse amplitude drive signal, this predetermined drive parameter indicates the amplitude of the drive signal including the sign thereof. For a pulse time modulated drive signal, the predetermined drive parameter indicates the duration and sign of the pulse making up the drive signal. For a hybrid generation or pulse-shaped drive signal, the predetermined drive parameter indicates the amplitude and the length of portions making up the drive pulse.

Note that this invention may be implemented in passive matrix as well as active matrix electrophoretic displays. In fact, the invention can be implemented in any bi-stable display that does not consume power while the image substantially remains on the display after an image update. Also, the invention is applicable to both single and multiple window displays, where, for example, a typewriter mode exists. This invention is also applicable to color bi-stable displays. In a color bi-stable

display, the grayscale is to be understood as that any intermediate state between two extreme colors. Also, the electrode structure is not limited. For example, a top/bottom electrode structure, honeycomb structure or other combined in-plane-switching and vertical switching may be used.

Finally, the above-discussion is intended to be merely illustrative of the present invention and should not be construed as limiting the appended claims to any particular embodiment or group of embodiments. Each of the methods and apparatuses utilized may also be utilized in conjunction with further systems. Thus, while the present invention has been described in particular detail with reference to specific exemplary embodiments thereof, it should also be appreciated that numerous modifications and changes may be made thereto without departing from the broader and intended spirit and scope of the invention as set forth in the claims that follow. The specification and drawings are accordingly to be regarded in an illustrative manner and are not intended to limit the scope of the appended claims.

In interpreting the appended claims, it should be understood that:

a) the word "comprising" does not exclude the presence of other elements or acts than those listed in a given claim;

b) the word "a" or "an" preceding an element does not exclude the presence of a plurality of such elements;

c) any reference numerals in the claims are for illustration purposes only and do not limit their protective scope;

d) several "means" may be represented by the same item or hardware or software implemented structure or function; and

each of the disclosed elements may be comprised of hardware portions (e.g., discrete electronic circuitry), software portions (e.g., computer programming), or any combination thereof.